

Path Planning for the Pragyan Rover: Experiences and Challenges

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Abstract—The Chandrayaan 3 mission, orchestrated by the Indian Space Research Organisation, achieved historic milestone by landing near the moon's south pole. A significant feat of this mission was the inaugural extraterrestrial mobility operation employing the Pragyaan Rover, nested within the Vikram Lander. This paper details the semi-autonomous ground-based path planning operations, challenges faced and strategies pivotal to the rover's mobility endeavors and scientific exploration on the lunar surface. Pragyaan Rover embarked on a multifaceted mission, conducting in-situ scientific experiments, gathering crucial data, and enabling lunar surface mobility. Ground based Rover Path Planning (RPP) software formed the backbone of the rover's expedition, meticulously planning paths considering topographical constraints, scientific exploration priorities and rover safety. Challenges stemming from the unique operational environment and the rover's constrained mission duration necessitated strategic approaches to ensure continuous data collection, efficient mobility, and timely scientific experimentation. The successful execution of Pragyan RPP operations, the triumphs and lessons learned lay the groundwork for more complex future missions.

I. INTRODUCTION

Indian Space Research Organization (ISRO) landed near the south pole of the moon on 23 August 2023 with its Chandrayaan 3 mission. The mission's primary objectives[1] were threefold: 1) Demonstrate safe and soft landing on the lunar surface with its Vikram lander 2) Carry out lunar mobility operations using the Pragyan Rover (stowed inside the Vikram lander) 3) To conduct in-situ scientific experiments and relay the data to ground [1]. The mission's difficulty was exacerbated by the fact that this was the first time the organization was carrying out scientific experiments and mobility operations on an extraterrestrial body. The novelty of RPP operations, coupled with the short duration of the mission (planned for a single lunar day) and the need to collect as much science data as possible - necessitated the RPP team to operate around the clock.

Pragyan is a lightweight rover, measuring $1m \times 1m$ and weighing 26 kilograms. The rover is equipped with a pair of fore-facing, fixed stereo cameras for navigation (NavCam). It also features an imaging camera in the aft section, looking at the tracks and dug out soil left by the rover. The mobility system consists of six 18cm diameter wheels in a rocker-bogie configuration. All six wheels could be driven independently, but none of them could be steered. The generated path thus consisted of straight lines and in place turns (by skid steering). The rover used wheel odometry to determine its current location and was commanded at a maximum speed

of 1 cm/s (36 m/hr) on straight paths. The turning rate was restricted to 1.2 deg/s. The rover chassis had a clearance of 10 cm from ground and thus any protrusion over 5 cm was treated as an obstacle. It was powered with a fixed vertical solar panel, which was deployed before the rover rolled down the lander's ramp.

While the team quickly adapted to the novelty of RPP operations, there were several factors which posed impediments in the path planning process: Improper sun angle knowledge and varying illumination (the sun azimuth was changing at a rate of 13° per day) and the tussle between maximizing science return vs rover mobility. The rover operations team had to deal with these and many such situations while the clock was ticking. Typical turn around time of rover path planning operation, which begins from acquiring NavCam images and ended with Rover's mobility, was around approximately 4 to 5 hours.

In Section II we describe the semi-autonomous path planning chain, section III describes the criterion for the safe path. Subsection III-A gives an example of the path's feasibility in terms of parameters corresponding to the mentioned criterion. Subsection III-B elaborates on the Inverse Kinematics model used to compute rover attitude as it traverses on the uneven terrain. Section IV describes the entire Rover Mobility Operation on the Lunar surface, which is divided into three drives which highlight major challenges, which are as follows: 1) IV-A states the need for retrace maneuver on encountering a big crater, 2) IV-B elaborates the requirement for reverse driving to ensure sufficient power generation & 3) IV-C describes the close prediction of Rover attitude on high slope terrain. Section V summarizes the milestones of Pragyan's Lunar surface mobility.

II. GROUND PATH PLANNING CHAIN

The rover path planning operations were semi-autonomous, with human operators required for each mobility. An overview of the ground-based software for planning rover mobility can be seen in Figure 1. The stereo images from the navigation cameras were used to create a Digital Elevation Map (DEM) of the photographed terrain (as generated by SAC Team). The DEM is a representation of the terrain, with 1 cm resolution. The Mission module was responsible for providing the destination for each mobility and the required sun angle for parking the rover. The rover parking angle ensures that the rover has adequate power between mobilities. The Mechanism module was responsible for providing translational and rotational slip information. Slip is used for computing each mobility

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segment's duration.

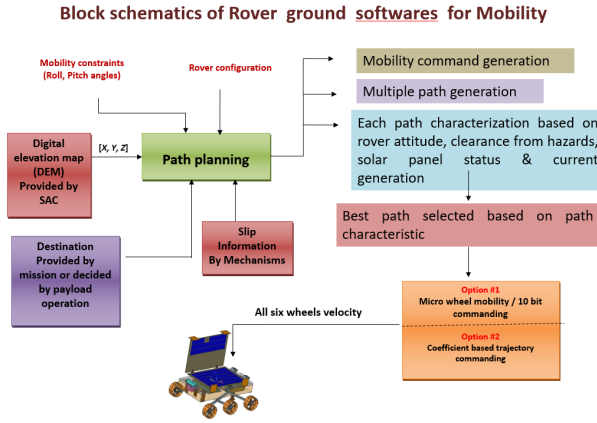


Fig. 1. Schematic of the ground based Path Planning Software

The Path Planning module received the terrain DEM, destination, solar parking angle, mobility constraints and slip information as inputs and computes the rover path that avoids obstacles along the way. The RPP software identifies "obstacles" in the DEM based on the rover chassis clearance. The final obstacle selection was done by the human operator based on obstacles indicated in the DEM (by the software) and NavCam images. The generated path also satisfies the criterion mentioned in the next section.

Typical mobilities were planned to cover a distance of 5 meters each, as this was the distance up to which the generated DEM was reliable, i.e. DEM had a resolution at which obstacles bigger than 5cm could be detected. Once the path was finalized, the software would compute the respective wheel speeds that would be required to traverse on the computed path. Velocity command for the computed path would then be uplinked. The rover would reach the new destination, conduct science experiments and take images for deciding the next science destination and mobility.

III. ROVER PATH PLANNING OVERVIEW

The objective of rover path planning is to generate a safe path from source to destination by ensuring that the rover roll & pitch angle is within safe limits to avoid toppling of rover. The path should satisfy other criteria like solar current not dipping to zero and minimum clearance from known hazards. The path generated satisfies the following criterion

- Rover roll and pitch do not exceed their design bounds ($\pm 15^\circ$) at any point in the entire path
- Avoid pebbles/boulders (size $> 5\text{cm}$) that violate the chassis clearance criteria.
- Maintain a minimum "safe" distance (5cm & above sized boulders & craters) from the identified obstacles, as well as the edges of the obtained DEM.
- Ensure that solar power generation (dictated by the solar panel string current) does not drop below the minimum level throughout the planned path.

The feasibility file generated by the RPP software provides a concise summary of path characteristics, focussing on the criteria mentioned above (Figure 3). It displays key parameters related to rover safety, mobility and power generation. In instances where the RPP software generates multiple paths for a single DEM, the optimal path is chosen based on the priority assigned to the above four criteria [6]. This process ensures a thorough evaluation of safety and power generation aspects in determining the most suitable path.

A. A Typical Drive

The sequence of operations carried out for path planning will be illustrated here using data from the second mobility carried out post deployment. Each planned mobility was assigned a unique mobility ID. As only a single pair of stereo cameras is available for imaging and navigation, the generated DEM (Figure 2a) is V shaped, which is narrow near the rover and expands as we move away. The RPP software computes the blind zone as the region where DEM width is less than rover's width, marked as end of first segment on the DEM (Figure 2b). The rover is driven in straight line until the last pair of wheels cross the blind zone. The area near DEM edges is to be avoided (fringe area) and is delineated with a red dashed line (Figure 2b). The fringe is computed to ensure rover never crosses the DEM boundary even after slipping.

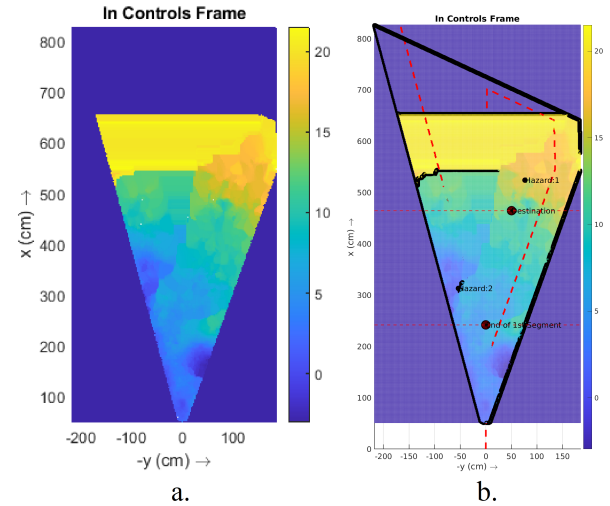


Fig. 2. Mobility 2: DEM, a. Input received, b. DEM with identified obstacles & high slope region (as marked black)

Using the DEM, the rover path planning software first runs a high slope detection algorithm and then uses it to identify potential hazards (Figure 2b). This is followed by selection of Waypoints through which the rover must pass. Once these inputs have been confirmed, the Path planning software computes the rover trajectory as explained earlier. A Feasibility file is generated to check if the computed path is feasible for mobility (Figure 3). It consists of three major sections - Segment-wise mobility summary, Segment-wise power summary and Segment-wise Rover attitude & Obstacle clearance.

The first section in Figure 3 tells that the computed path consists of four segments: a 2.76 m straight drive (To clear the blind zone in the DEM), a 12.713° CW (clockwise) turn (To turn towards the destination and steer away from Hazard 2), a 2.283 m straight drive to reach the destination and a final 24.465° CCW (counter-clockwise) turn for solar parking. The segments are numbered as per their order of execution and the segment number is used to track the type of mobility.

The second section is used to check whether adequate solar power is being generated when the rover traverses the computed path. We generate an estimate of the power generation based on the incident sun angle and the rover orientation. The power generation happens on both the back side of the panel (the side which faces the rover) and the front side. While the front side is fully populated with solar cells and generates 2.7 A at full capacity, the backside is only partially populated and generated 0.9 A at full capacity (as per Power Systems Group). The backside and frontside power generation is denoted by S1 string, S1&S2 string respectively. Maximum power generation occurs when sunlight is directly incident on the front side of the panel (S1&S2 solar current generation in Figure 3).

The third section is used to check if the roll-pitch angles on the computed path are within allowable limits (Figure 3). The simulated roll-pitch plots can be seen in Figure 4. The roll-pitch angles are derived based on the inverse kinematics model described in section III-B. The rover tends to deviate from the commanded path due to slip and hence sufficient margin from hazards has to be ensured for the generated path. The minimum distance of the rover from the identified hazards was also computed in each segment.

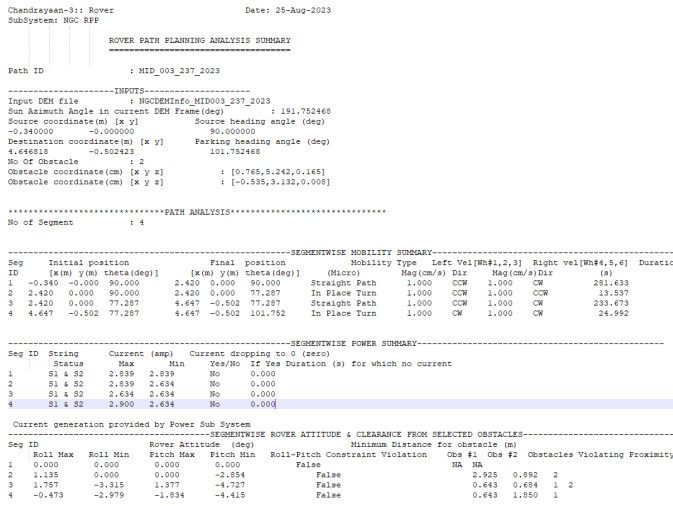


Fig. 3. Mobility 2: Feasibility File

Feasibility files were generated for multiple acceptable paths. The best path was selected by the operator based on the constraints mentioned in the second & third section of the feasibility file. Only after all of the above checks, the final path was selected.

Once the path is decided, a path command file is gener-

ated, which contains wheel velocity and the duration of each segment. The duration is worked out based on the slip to account for velocity loss due to slippage. Slip estimate was computed based on ground testing on Lunar soil simulant. Lastly, the command file is provided to the Mission for uplinking to the rover.

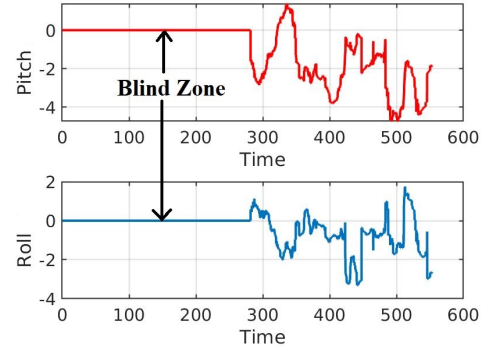


Fig. 4. Mobility 2: Rover Roll-Pitch angle Estimate (degrees)

B. Inverse Kinematics

The roll, pitch angle is computed based on the inverse kinematic model [2]-[5]. The input to the inverse kinematic model is the terrain map and rover configuration. The kinematics parameters which defines the rover attitude and the rover frame is shown in Figure 5. The configuration and the

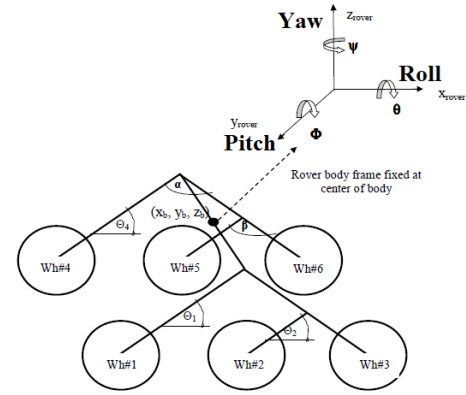


Fig. 5. Rover Schematic [5]

position of the rover is fully defined by ten parameters - (1) The position of the center of the body is defined by (x_b, y_b, z_b) (2) The rover orientation is defined by (ψ, θ, ϕ) for the yaw, roll and pitch respectively and (3) The configuration of the bogie mechanism is defined by the angles $(\theta_1, \theta_2, \theta_4, \theta_5)$. The solution is derived from the basic assumption that all six wheels are in contact with terrain. Hence six closed loop equations are constructed and the set of kinematic parameters which satisfies this constraint is the rover attitude [3],[5]. The inverse kinematic problem is solved using geometric approach. As seen in Figure 4, the computed rover roll-pitch angles for this mobility are well within the 15° permissible limit. Using DEM data, the x, y, z coordinates of all wheels

are computed based on the reference wheel. As seen in Figure 2 for the initial 2.5m the DEM width is less than rover width (Denoted by the end of first segment marker). This region is the blind zone for rover as terrain data is not available for all wheels. Hence there is no roll, pitch angle computation for the blind zone. The traversal through the blind zone is also reflected in Figure 4, where for the initial 250 s roll, pitch angle is zero. The actual variation in roll-pitch angles (as per inclinometer telemetry) is shown in Figure 6. The inclinometer measures the rover roll and pitch angles. Towards the end, the actual roll-pitch angles deviate from the estimate as they are based on the true trajectory traversed by the rover, which in turn has deviated from the commanded path due to slippage.

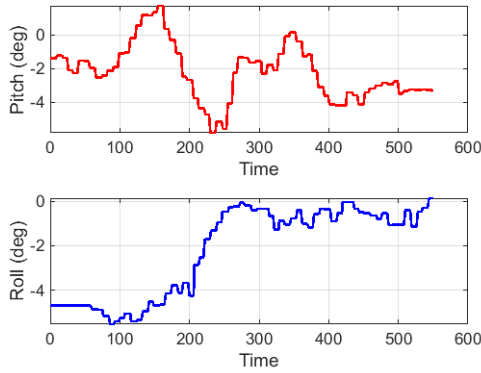


Fig. 6. Mobility 2: Rover Roll-Pitch as per inclinometer sensor

IV. ROVER MOBILITY OPERATIONS

The rover operations were initiated on 23rd August (during first lunar day), post landing and settling of the lunar dust. The landing site images taken by the Chandrayaan-2 OHRC (Orbiter High Resolution Camera) were used in arriving at the destination, however they were not part of the ground path planning chain. The rover mobility operations consisted of three major drives - South drive, Westward drive and Parking drive. The first drive was towards a crater to the south of the landing site (Figure 7). The second drive was targeted at a relatively "fresh" crater that was identified by the science team. This crater was to the west of the landing site. The final drive was primarily aimed at finding a suitable location to park the rover when the lunar day ended, whence both the lander and rover would go into sleep. The rover track in Figure 7 was reconstructed based on the uplinked commands, estimated slip and rover location as seen in OHRC images taken after onset of second lunar day (on 20th September 2023) after landing.

A. South Drive

Following the rover rolldown, the lunar terrain was imaged and ground-based path planning was commenced. The OHRC image indicated a crater to the south of our landing site, which was of interest to the science team. The drive consisted of several dogleg mobilities, one of which (Mobility

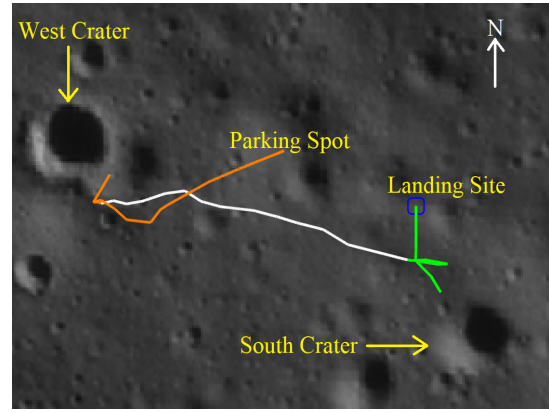


Fig. 7. Reconstructed Rover track. Green: South Drive, White: Westward Drive, Orange: Parking Drive

2) has already been explained in Section III-A. After several mobilities, the rover reached the south crater (Figure 8).

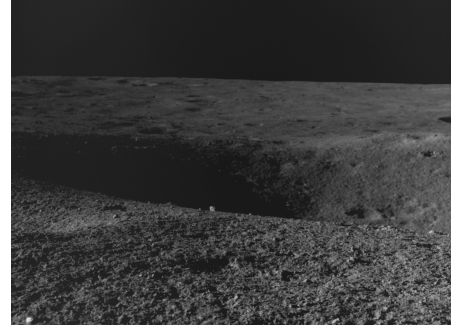


Fig. 8. Crater in the south

Taking multiple in-place turns by the rover for panoramic imaging (Figure 9) dug up the lunar terrain which proved to be helpful for science data collection. However turning at the same location could result in the rover sinking in that place and thus no further movement towards south was planned. The rover was driven in reverse towards the lander in Mobility 6. For the mobility corresponding to the feasibility file in Figure 3, the reverse drive commanded was 24.465 deg CW, 2.283 m in reverse, 12.713 deg CCW and another 2.76 m in reverse. The wheel tracks created by these forward and reverse drives can be seen in Figure 9. Driving in reverse along the same track also helped in visualising the slip on lunar terrain.

Another mobility towards the East was carried out to study the tracks of rover wheels on lunar terrain. Mobility 11 was parallelogram like, executed to preserve the wheel tracks and return to the starting position. The preserved tracks were then imaged using the rover Navcams. The mobility consisted of a forward dogleg maneuver and a reverse dogleg maneuver that completes the parallelogram (Figure 10). The next target was to sample a relatively "fresh" crater towards the west.

B. Westward Drive

The relatively "fresh" crater to the west was identified based on the OHRC image. By this time the sun had moved

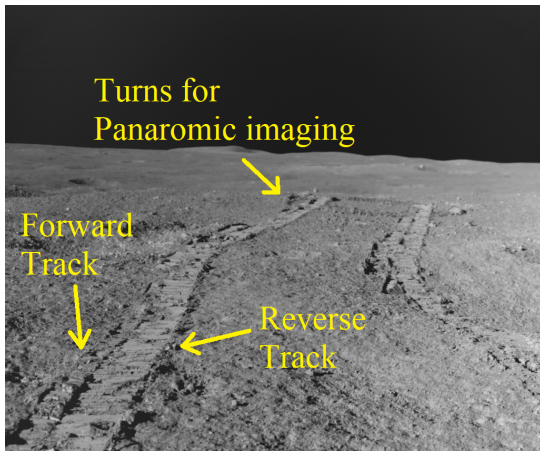


Fig. 9. Mobility 6: Retrace Maneuver after encountering crater in the south

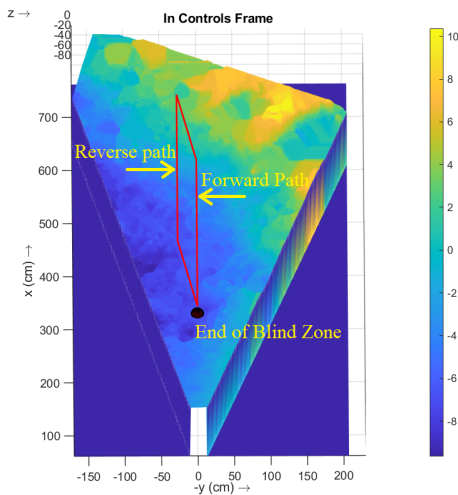


Fig. 10. Mobility 11: Parallelogram mobility for wheel track imaging

from east to north and would continue moving westward. Due to the need to turn the body-fixed solar panel towards sun and the science mandate to move towards the west (while ensuring continual power generation throughout the movement and parking), the westward drive was primarily done by driving in reverse ("moonwalking" maneuver). This reduced the rate at which new terrain was traversed. A sample mobility done during the westward drive (Mobility 28) is detailed below to show the need as well as the implementation of reverse driving. The rover Navcam took these images facing west. The Navcam image, generated DEM and the computed path for Mobility 28 can be seen in Figure 11. We see that the path planning software computes two hazards in the DEM (Figure 11). The path is planned with a waypoint in between to avoid those hazards and reach destination. The computed path thus consists of 6 segments in total, three straight drives and three in place turns. The final in-place turn is for solar parking. However, due to the position of the sun and the placement of the rover's solar panel, this mobility would have only exposed the inner side

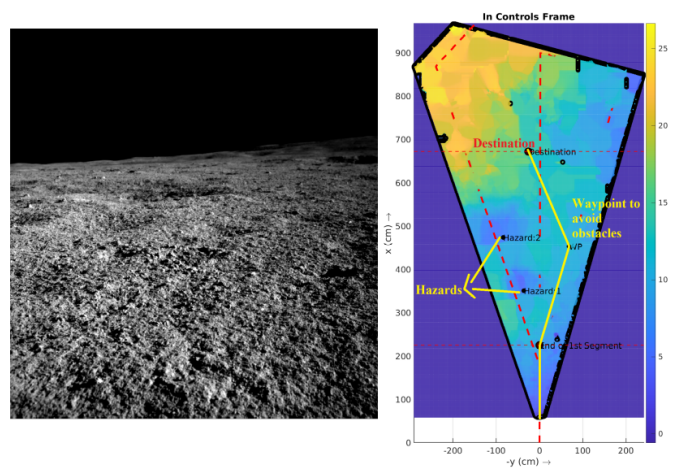


Fig. 11. Mobility 28. Left: Navcam image, Right: Computed Path

of the panel to the sun. This would lead to lower solar current generation (only S1 illuminated as seen in Figure 12) as opposed to the nominal current generation (S1&S2 illuminated). Hence the rover was driven in reverse to ensure both S1&S2 were illuminated.

When computing the commands to be sent for driving in reverse, only the straight segment commands were changed (i.e. straight ahead became straight reverse). However the rotation commands (CW/CCW turns) remained the same due to invariance of the rotation axis (Z axis in Figure 5).

SEGMENTWISE POWER SUMMARY						
Seg ID	String	Current (amp)	Current dropping to 0 (zero)	Yes/No	If Yes Duration (s)	for which no current
1	S1	0.636	0.636	No	0.000	
2	S1	0.636	0.422	No	0.000	
3	S1	0.422	0.422	No	0.000	
4	S1	0.634	0.422	No	0.000	
5	S1	0.634	0.634	No	0.000	
6	S1	0.634	0.634	No	0.000	

Current generation provided by Power Sub System

Fig. 12. Mobility 28: Section 2 of Feasibility File

The "moonwalking" maneuver consisted - a. taking an image, b. path planning c. driving in reverse on the planned path , d. turning 180 degrees and image to plan the next path (thus starting a. again). There was a translational motion between subsequent in-place turns to avoid rotations at the same location. Although the reverse driving did cost us several extra turns in each movement, facing east helped us utilize the lander as a "buoy". On reaching the crater, we collected science data near its periphery. As only two days were left till the sunset (End of Mission), the objective was to traverse as much new terrain as possible and keep sampling, while also looking for a suitable location to park the rover for sleep.

C. Parking Drive

With the primary science objectives completed, the final parking location of the rover was to be chosen such that the roll/pitch angles were nearly zero, there was a sufficiently flat terrain ahead and the body-fixed solar panel was facing east - prepared for the next lunar day. With sun in the west, the lunar terrain right ahead was brightly illuminated. This restricted any further mobility towards the west and after extensive imaging, a north-east drive was planned. The rover

encountered a declivitous terrain in the north-east drive, and multiple images were taken before planning each mobility. During the drive there were situations where the planned path would need the rover to drive at roll/pitch angles above the safe limit. One such instance happened in Mobility 42, the computed roll-pitch plots as per the inverse kinematics can be seen in Figure 13. We see that the roll angle has well exceeded the 15° limit. However with sloped terrain all around - the mechanism team approved this mobility and the rover drove through the high roll landscape for a few mobilities. The actual roll variation (Refer Figure 5 for axis definition) as per the received telemetry can be see in Figure 14. The maximum roll angle observed in predicted and actual plots match closely. The segment delays in Figure 14 were used for imaging the lunar terrain, which was especially needed for path planning in the sloped terrain. This mobility consists of 4 segments and the duration of each segment is indicated in Figure 14 using a segment counter - which takes values from 1 to 4. After a few treacherous mobilities, the rover was finally able to reach flat terrain, suitable for putting the rover in sleep mode.

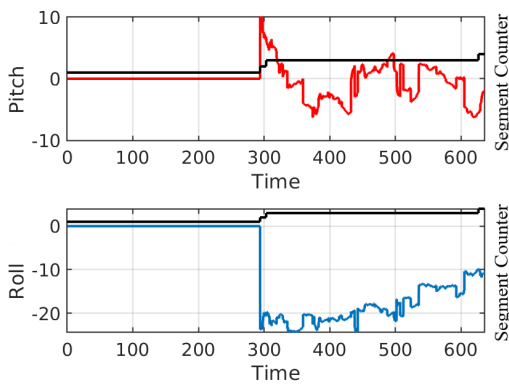


Fig. 13. Mobility 42: Predicted Roll variation (degrees). Black plot - segment counter

V. CONCLUSIONS

The Rover traversed a distance of more than 100 metres in 10 days, went to sites that were of interest to the science team. The RPP operations encountered a lot of unforeseen difficulties, which had to be resolved on the fly. Several new mobility strategies were devised, tested and implemented such as retrace, driving in reverse and parallelogram drive. The rover was able to safely and successfully complete the planned science operations and was ultimately parked with its solar panel facing east, hoping for revival when the sun would rise again after 14 days.

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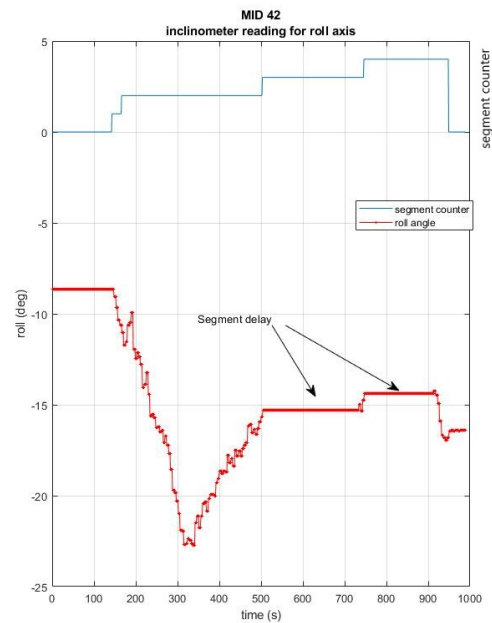


Fig. 14. Mobility 42: Actual Roll variation. Blue plot - segment counter

Director (Controls and Digital Area) for their unending support during the mission. Teams from Space Applications Centre (SAC), Spacecraft Mechanisms Group (SMG), Control and Digital Electronics Group (CDEG), NavCam and inclinometer team (LEOS) and Mission Planning and Operations Group (MPOG) were crucial to the lunar mobility operation and worked in tandem with the Controls team for the successful completion of the mission objectives. This mission was a gargantuan undertaking, with thousands of scientists and technicians from all ISRO centres dedicating several years of continual effort. We would like to thank and acknowledge everyone who worked on Chandrayaan-3 and the previous missions leading up to it.

REFERENCES

- [1] https://www.isro.gov.in/Chandrayaan3_Details.html
- [2] Rima Ghosh, Bharat Kumar G.V.P., and Ravi Kumar L, P. Natarajan, K Parameswaran, P. J Bhat, "Inverse Kinematic Analysis of a 4 wheel Rover motion on uneven terrain", National Conference on Space Transportation System, VSSC, 2011.
- [3] Chottiner, J.E., "Simulation of a Six- wheeled Martian Rover called Rocker-Bogie", M.S Thesis, The Ohio State University, Ohio, 1992.
- [4] K. Iagnemma and S. Dubowski, "Vehicle-ground contact angle estimation with application to mobile robot traction", Proc. 7th Int. Conf. on Advances on Robot Kinematics, Ark '00, pp. 137-146, 2000.
- [5] Farritor, S., Hacot, H., Dubowsky, S., "Physics-Based Planning For Planetary Exploration", IEEE International Conference on Robotic and Automation, 1998.
- [6] Rima Ghosh, G.V.P Bharat Kumar, Sumithra Kakanuru, Rijesh M.P, Harish Joglekar, Dr M.S Siva, Ritu Karidhal, "The impact of slip and rover mobility implementation constraints on planetary rover path planning", 2022, 73rd International Astronautical Congress (IAC), Paris, France.
- [7] J. J. Craig, Introduction to Robotics, 2nd Ed, Adelson-Wesley Publishing, 1989
- [8] M. G. Bekker, Introduction to Terrain-Vehicle Systems, University of Michigan Press, 1969